VEHICLE DESIGN PARAMETER STUDY FOR SIDE IMPACTS USING FULL VEHICLE SIMULATION

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ABSTRACT

This paper describes a study that was conducted to determine sensitivity of several design factors for reducing injury values of occupants upon side impact using Taguchi method. The full mid-sized vehicle finite element model is used for the analysis under two different side impact standards - SINCAP and ECE-R 95. The design factors that may have major effect on side impacts were selected and L_8 orthogonal array was set up for analysis.

Analysis results show that strengthening the passenger compartment improve occupant protection, especially adding a pusher foam is significantly lowering the injury values in SINCAP. No single factor has major effects on rib deflection which is considered as critical occupant injury criterion in ECE-R 95.

Taguchi method was found to be a useful tool, although its usage may be limited in crash analysis, for predicting the effect of various design factors on structure.

INTRODUCTION

Currently, vehicle manufactures are confronted with two different international standards(FMVSS 214 & ECE-R 95) for the dynamic side impact test. In this respect, vehicle manufactures put a lot of efforts to develop their vehicles that meet the requirements of both existing standards. The problem is that these standards differ not only in their test conditions but also in the construction of dummies and its injury criteria. Moreover, those who design cars to meet the European side impact standard have experienced more difficulty than they expected since 'conventional wisdom' which is applied to meet Federal Motor Vehicle Safety Standard(FMVSS) 214 standard and has proven to be worked is ineffective to meet ECE-R 95 standard[1]. Therefore, a study was initiated to gain a better understanding of how design factors on vehicle structure affect on these standards.

To evaluate the effects of all design factors on side impact using 'one-factor-at-a-time' methods would require a large number of case studies. As an alternative, the Taguchi method was considered. The time and costs required for analysis would be substantially reduced by using this method, but its use in crash analysis is very limited. Such a detailed approach of all steps in Taguchi method would not be cost and time-effective for full vehicle finite element model analysis. Therefore, a study was designed with a simplified Taguchi method. In this study, mean analysis approach was used rather than signal-to-noise(S/N) ratio approach. Also, the optimum setting of design factors and confirmation analysis were not performed here.

USE OF TAGUCHI METHOD

In this study, Taguchi method is being utilized to determine sensitivity of several design factors for side structure. The design factors that may have major effects on side impact were selected and L_8 orthogonal array was set up for analysis. The factors selected for the study included door outer pusher foam, rocker reinforcement extension, B-pillar reinforcement, door trim padding, floor cross-member front, floor cross-member rear and B-pillar reinforcement lower. These factors and their chosen number of levels are listed in table1.

Table 1.
Design Factors

Label	Factor	Levels	
A	Existence of pusher foam	1	2
B	Rocker reinforcement extension	1	2
C	Upgrade of B-Pillar reinforcement thickness	1	2
D	Existence of door trim padding	1	2
E	Existence of floor cross-member front	1	2
F	Existence of floor cross-member rear	1	2
G	Existence of B-pillar reinforcement lower	1	2

Table 2 illustrates the L_8 orthogonal array formats that was used in this study[3].

Table 2.
L_8 Orthogonal Array

	A	B	C	D	E	F	G
	1	2	3	4	5	6	7
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

In accordance with L_8 orthogonal array, the full mid-sized vehicle finite element model(Fig. 1) is modified and used for analysis under two different side impact standards - SINCAP and ECE-R 95.

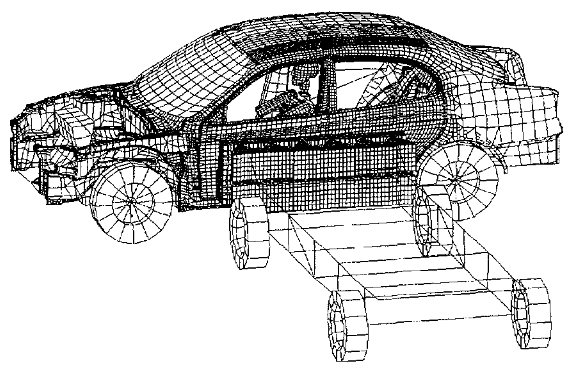

Figure 1. Full Vehicle Finite Element Model

A series of analysis was carried out to investigate the effects of design factors which would be major effect on occupant injury under side impact. Two standards were involved in this study - SINCAP and ECE-R 95.

SIDE IMPACT NEW CAR ASSESSMENT PROGRAM (SINCAP)

In 1997, The National Highway Traffic Safety Administration(NHTSA) releases side impact crash test results. These results brought enough attention to auto makers since their vehicles on the market are selected and being tested under severer condition than FMVSS214 and their results are published to consumers. According to the NHTSA's test results, just 15 percent of 17 tested cars earned four stars - none scored five stars[2]. The agency suspects that such publication will give auto makers a motivation to improve side crash protection in their vehicles just as the frontal crash protection score increases 83 percent high, equivalent to four or five stars, from 28 percent when its test was first started.

The SINCAP crash test simulates a typical intersection collision between two vehicles. Forces are measured on two crash dummies when moving deformable barrier(MDB) is 27 ° angled into the side of car at 38.5mph(Fig. 2). This is 5mph faster than the speed regulated in compliance with FMVSS214.

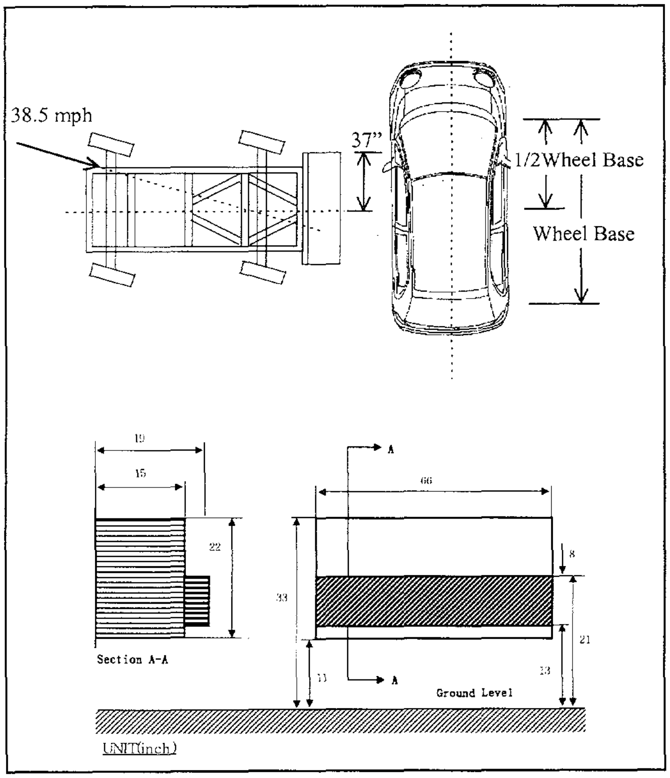

Figure 2. SINCAP Test Condition.

For injury criteria, star ratings are assigned as follows,

★★★★★	TTI ≤ 57
★★★★	57 < TTI ≤ 72
★★★	72 < TTI ≤ 91
★★	91 < TTI ≤ 98
★	98 < TTI

Fill Vehicle Test

In order to see how 5mph difference will affect the crashworthiness of vehicle and injury criteria, tests were performed with different impact speed conditions.

Figure 3 shows the comparison of occupant injuries between FMVSS214 and SINCAP. As it can be clearly seen in this figure, the injury values are dramatically increased, almost twice for rear dummy, for 5mph difference crash speed. Therefore, it would not give satisfactory results in SINCAP test if auto makers only develop their car to meet FMVSS214 requirements.

Also, the conventional wisdom such as strengthening the passenger compartment and restraint system that applied to meet FMVSS214 would work for SINCAP remains in question. This is the one of main reasons for using SINCAP test conditions for the study. The study will give design requirements, in detail, for comprehensive side protection in SINCAP.

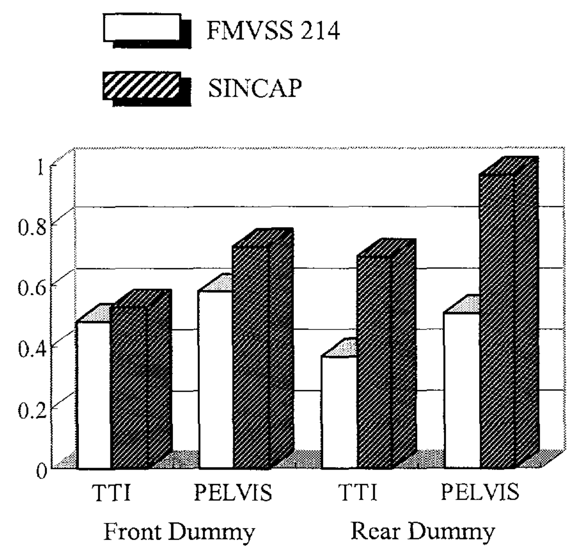

Figure 3. Injury values for FMVSS214 and SINCAP

Full Vehicle Model Structural Computation

Figure 4 shows the deformed vehicle structure from the computational results of base model(case 2) and 7 additional analyses were performed in accordance with orthogonal array.

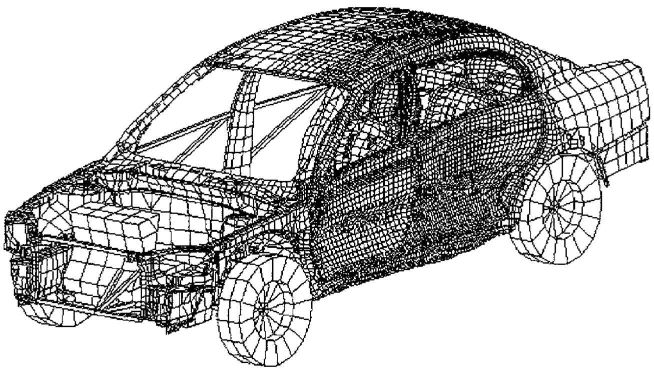

Figure 4. The Deformed Vehicle Structure, SINCAP

The injury values of SINCAP from eight compositions are presented in table 3 and 5, front and rear dummy respectively. Response tables based on mean analysis were calculated to identify the most significant control factors. Table 4 and 6 show the contribution of the control factors in analysis results. The results are classified as "the bigger variation of between two levels, the more effects on side impact ."

Analyses Results for Front Dummy

The most significant control parameter influencing TTI is pusher foam in SINCAP, which accounted for 11.7% of the mean variation. The rest factors are accounted for less than 5% of variation. This is probably due to the fact that the most factors involve with strength of structures that below the H-point level. Upgrading of B-pillar reinforcement thickness (factor C) considered to affect on TTI values is less sensitive than expected.

For pelvis acceleration, pusher foam is also the most significant parameter producing 23.1% of the variation, followed by floor cross member rear, and B-pillar reinforcement at 16.5% and 11.2%, respectively. Overall, all factors can be effective for lowering pelvis acceleration, and optimal setting would give more reduction.

Table 3.

Normalized analysis result for front dummy

	Lower Spine	Upper Rib	Lower Rib	TTI	Pelvis
1	1.10	0.98	1.05	1.07	1.34
2	1.00	1.00	1.00	1.00	1.00
3	0.98	1.03	0.99	1.01	0.93
4	1.01	0.99	0.92	1.00	1.05
5	0.90	0.77	0.82	0.85	0.89
6	0.93	0.90	0.83	0.92	0.77
7	0.96	0.84	0.86	0.91	0.83
8	0.89	0.98	0.81	0.93	0.91

Note : Case 2 is Base Model

Table 4.

Response Table for Front Dummy

TTI

	A	B	C	D	E	F	G
1	1.020	0.960	0.978	0.960	0.982	0.966	0.974
2	0.903	0.962	0.944	0.963	0.941	0.957	0.936
Delta	0.117	0.002	0.034	0.003	0.041	0.009	0.038

Pelvis

	A	B	C	D	E	F	G
1	1.081	1.000	1.021	0.999	0.989	1.048	0.997
2	0.850	0.931	0.909	0.932	0.942	0.883	0.889
Delta	0.231	0.069	0.112	0.067	0.047	0.165	0.108

Analyses Results for Rear Dummy

Pusher foam does not take into accounts for rear dummy since it was only applied to front door. The control parameter influencing TTI is B-pillar reinforcement, which accounted for 6.2% of the mean variation. Similarly, 5.4% of the variation was due to floor cross member rear and 5.0% was due to floor cross member front.

For pelvis acceleration, door trim padding was the most significant parameter producing 24.8% of the variation, followed by floor cross member front , and floor cross member rear at 9.5% and 8.8%, respectively.

From results above, every factor has some degree of sensitivity to the occupant injury. Specially, adding a pusher foam or door trim padding are substantially effective to lowering both TTI and pelvis acceleration.

Table 5.

Normalized analysis results for rear dummy

	Lower Spine	Upper Rib	Lower Rib	TTI	Pelvis
1	0.97	1.15	0.89	1.00	1.35
2	1.00	1.00	1.00	1.00	1.00
3	1.16	0.90	0.87	1.00	1.39
4	0.87	1.02	0.82	0.89	1.05
5	0.95	0.88	0.80	0.87	1.10
6	0.86	1.19	1.02	0.97	1.13
7	1.09	1.03	0.88	0.99	1.36
8	0.94	1.01	1.02	0.98	1.03

Table 6.

Response table for rear dummy

TTI

	A	B	C	D	E	F	G
1	N/A	0.960	0.993	0.964	0.987	0.935	0.962
2	N/A	0.964	0.931	0.960	0.937	0.989	0.968
Delta	N/A	0.004	0.062	0.004	0.050	0.054	0.006

Pelvis

	A	B	C	D	E	F	G
1	N/A	1.145	1.184	1.300	1.223	1.132	1.222
2	N/A	1.207	1.167	1.052	1.128	1.220	1.168
Delta	N/A	0.062	0.017	0.248	0.095	0.088	0.054

EUROPEAN SIDE IMPACT (ECE-R 95)

ECE-R 95 test involves a side collision with EURO-Moving Deformable Barrier at an angle of 90 ° and a test speed of 50km/h. Its impact position to the target vehicle is relative to the seating position of the driver, R-Point, shown in Figure 5.

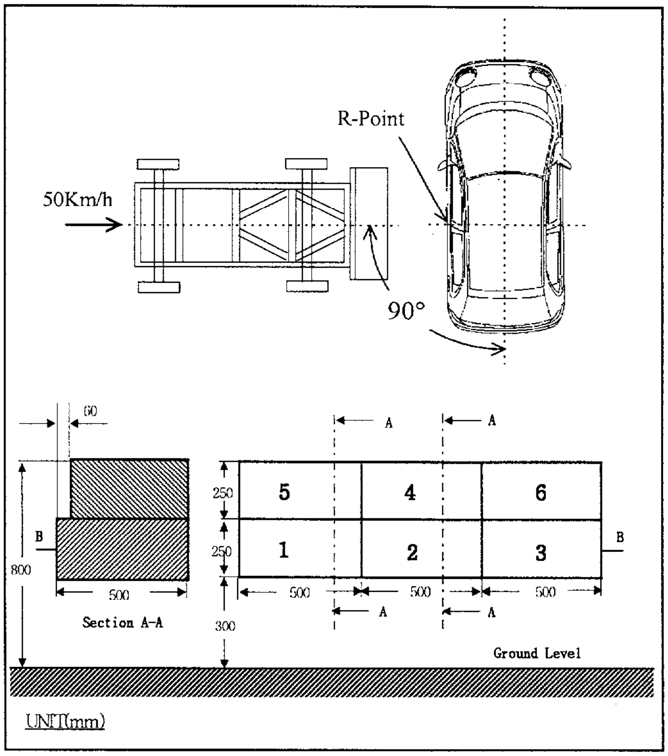

Figure 5. ECE-R 95 test condition.

The dummy used in ECE-R 95 is EUROSID dummy and its injury criteria cover maximum acceleration level to the head, rib deflection limits and peak forces to the abdomen and pelvis as follow,

Criteria for ECE-R 95		
Head	HPC	< 1000
Thorax	Deflection	< 42 mm
	VC_{max}	< 1 m/s
Pelvis	PSFP	< 6.0 KN
Abdomen	APF	< 2.5KN

Full Vehicle Model Structural Computation

Figure 6 shows the deformed vehicle structure after impacting with European side impact test condition. It is also computational results of base model(case 2).

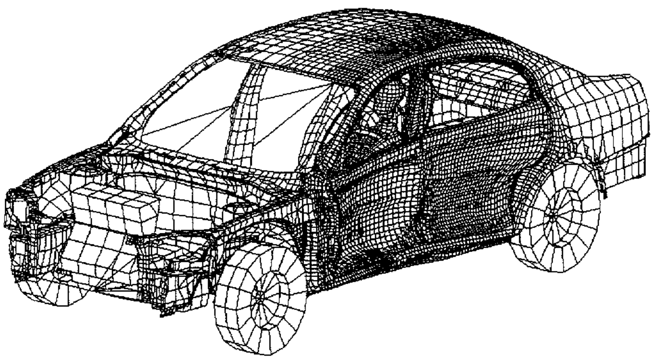

Figure 6. The Deformed Vehicle Structure, ECE-R 95

The injury values of ECE-R 95 from eight compositions are presented in table 7. Response tables were calculated to identify the most significant control factors. Table 8 shows the contribution of the control factors in analysis results.

Analyses Results

It is interesting to note that no single factor has significant effects on rib deflection which is considered as the most critical injury criterion in European side impact. However, strengthening the passenger compartment in lower level (factor E and F) slightly increase the rib deflection which is the conflicting results of federal regulation.

The effective control parameter for Viscous Criterion was a pusher foam which is accounted for 10.4 % of the variation. Even though floor cross member rear and B-pillar reinforcement lead 8.2% and 5.1% of variation respectively, it gives an adverse effects on injury values.

Eliminating factors which weaken the lower level of passenger compartment structure will give lower Viscous Criterion and rib deflection values. This result might be supporting the ideas that increasing the penetration of passenger compartment at the lower level relative to the upper will give significant reduction in thoracic loading[4]. It means that such a design concept should be made at the early stage of vehicle structure development in order to effectively fulfill the European side impact requirements.

Every factor has some degree of sensitivity to the abdomen and pubic forces, so it would not be any problems to control these injury values. Also analysis results show their injury values much lower than its requirements. These would not be considered as critical injury criteria .

Table 7.

Normalized analysis results

	Rib deflection	Rib V.C.	Abdomen Force	Pubic Force
1	0.89	1.02	0.78	0.94
2	1.00	1.00	1.00	1.00
3	0.96	1.08	0.99	1.11
4	0.93	1.04	1.06	1.08
5	0.94	0.86	0.96	0.99
6	0.91	0.96	0.96	1.20
7	0.92	1.05	0.83	1.07
8	0.94	0.85	1.00	1.24

Table 8.

Response table

Rib Deflection

	A	B	C	D	E	F	G
1	0.945	0.934	0.937	0.928	0.925	0.922	0.913
2	0.926	0.938	0.935	0.946	0.946	0.950	0.945
Delta	0.019	0.004	0.002	0.018	0.021	0.028	0.032

Viscous Criterion

	A	B	C	D	E	F	G
1	1.035	0.961	0.981	1.004	0.979	0.942	1.019
2	0.931	1.006	0.985	0.963	0.987	1.024	0.968
Delta	0.104	0.045	0.004	0.041	0.008	0.082	0.051

Abdomen Force

	A	B	C	D	E	F	G
1	0.960	0.927	0.903	0.893	0.933	0.952	0.908
2	0.938	0.972	0.995	1.005	0.965	0.945	0.958
Delta	0.022	0.045	0.092	0.112	0.032	0.007	0.049

Pubic Force

	A	B	C	D	E	F	G
1	1.032	1.031	1.064	1.027	1.122	1.063	1.072
2	1.124	1.126	1.093	1.130	1.035	1.094	1.101
Delta	0.092	0.095	0.029	0.103	0.087	0.031	0.029

CONCLUSION

The study was conducted to determine sensitivity of several design factors for reducing injury values of occupants under two different side impact conditions - SINCAP and ECE-R 95.

From SINCAP analysis results, every factor has some degree of sensitivity to the occupant injury. Specially, adding a pusher foam or door trim padding are substantially reducing both TTI and pelvis acceleration. However, the design principles should mainly focus on reducing TTI values since the injury values in SINCAP are based on TTI.

For ECE-R 95, no single factor can improve rib deflection which is considered as critical injury values. So, the major change of side structure would be required in such a way that increasing the penetration of passenger compartment at the lower level relative to the upper. Therefore, such a design concept should be made at the early stage of vehicle structure development in order to effectively fulfill the European side impact requirements.

As mentioned above, each factor has some degree of sensitivity to the occupant injury upon side impacts. Some factors are more sensitive than others and would give more effects on injury consequently. However, single factor can not solve the various requirements on side impacts. The proper combination of each factor will give more reliable results than single factor alone.

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